DOI: 10.1002/jsfa.2202

Kernel texture differences among US soft wheat cultivars†‡

Craig F Morris,[1]* Kim Garland Campbell[2] and Garrison E King[3]

[1]*USDA-ARS Western Wheat Quality Laboratory, Washington State University, Pullman, WA 99164-6394, USA*
[2]*USDA-ARS Wheat Genetics, Quality, Physiology and Disease Research Unit, 379 Johnson Hall, Washington State University, Pullman, WA 99164-6420, USA*
[3]*Department of Food Science & Human Nutrition, Washington State University, assigned to the Western Wheat Quality Laboratory, Pullman, WA 99164-6394, USA*

Abstract: Kernel texture is a key factor in the quality and utilization of soft wheat (*Triticum aestivum* L), yet the variation in kernel texture among US soft wheat cultivars is largely unknown. This study evaluated the following hypothesis: soft wheat cultivars differ in kernel texture due to minor genetic factor(s). Once identified, selected contrasting cultivars could serve as candidates for crop improvement and future genetic studies. To test the hypothesis, kernel texture (SKCS, Single Kernel Characterization System), NIR (near-infrared reflectance) and Quadrumat break flour yield were evaluated for 30 cultivars drawn from the four major US soft wheat regions and sub-classes (eastern and western soft white winter, soft red winter and Club). Cultivars were grown in replicated trials over 6 site-years in Washington state. The results clearly indicated that relatively large, consistent genetic differences in kernel texture exist among US soft wheat cultivars. SKCS and NIR were fairly well correlated ($r = 0.85$) and tended to rank cultivars in the same order. However, individual cultivars deviated from this linear relationship and occasionally rankings changed substantially. Trends were observed among the geographical regions and sub-classes, eg the first 13 hardest-ranked positions (SKCS) were held by western cultivars (13 of the 16 total western cultivars). Quadrumat break flour yield provided an independent assessment of kernel texture and was not correlated with SKCS or NIR hardness. Four distinct cultivar groupings were made based on analysis of variance and two-dimensional graphical assessment. Each group represented contrasting levels of kernel texture (SKCS or NIR) and break flour yield. Identification of the specific underlying gene(s) conferring kernel texture variation among US soft wheats awaits the next phase of research.

Keywords: grain hardness; kernel texture; wheat; Single Kernel Characterization System; near-infrared reflectance

INTRODUCTION

The quality and utilization of wheat (*Triticum aestivum* L) is highly dependent on kernel texture, or 'hardness'.[1] The qualitative kernel texture classes of the three major types of wheat in world commerce, soft hexaploid, hard hexaploid and durum, are determined by the presence/absence or allelic state of the *Hardness* locus and its underlying puroindoline proteins.[2] In this regard, soft wheats are regarded as uniformly possessing the soft *Ha* allele and the puroindoline genotype *Pina-D1a, Pinb-D1a*.[2] However, not all soft wheats exhibit an identical quantitative level of kernel texture. The source of this 'within-soft-wheat-class' variation is largely unknown and poorly characterized. Variation in kernel texture is also related to how the trait is measured. Kernel texture 'phenotype' is empirically, but routinely measured using PSI (particle size index), NIR (near-infrared reflectance spectroscopy), milling parameters such as break flour yield, and the SKCS (single kernel characterization system).[1–3]

In the USA, soft wheat is produced in two divergent regions: the eastern USA with production mostly east of the Mississippi River, or about 92 °W longitude, and the Pacific Northwest (PNW; comprising the states of Washington, Oregon and Idaho). Because each of these regions has a relatively long history of wheat cultivation and each is environmentally and geographically distinct, new cultivars have generally arisen from crosses made within each of the respective germ plasm pools. For example, Bacon[4] indicated that in eastern US breeding programs less than 10% of

* Correspondence to: Dr Craig F Morris, USDA-ARS Western Wheat Quality Laboratory, PO Box 646394, Washington State University, E 202 Food Science & Human Nutrition Facility East, Pullman, WA 99164-6394, USA
E-mail: morrisc@wsu.edu
†This article is a US government work and is in the public domain in the USA
‡Mention of trademark or proprietary products does not constitute a guarantee or warranty of a product by the US Department of Agriculture and does not imply its approval to the exclusion of other products that may also be suitable
(*Received 10 May 2004; revised version received 12 November 2004; accepted 27 January 2005*)

the germ plasm used in crossing was derived from lines with 'specific traits, other US wheat classes and foreign germ plasm.' In addition, the PNW produces two types of soft white wheat: soft white 'common' wheat with a lax (or 'common') spike, and Club wheat with a compact (or 'club-shaped' spike). These two morphological types are recognized as sub-classes in the US marketing system.[5] Crosses are typically more frequent between lines of the same sub-class than inter-class lines. For these reasons, it is reasonable to assume that eastern and western, and common and Club US soft wheat cultivars might represent different germ plasm 'bases,' and might therefore carry and exhibit minor differences in kernel texture (due to unknown minor, quantitative genetic differences). Similarly, it is generally recognized that soft wheat cultivars vary within a region and sub-class. Since agronomic practices, pathogens and insect pests change, cultivars developed over different time periods may represent different germ plasm bases as well.

Baenziger *et al*[6] compared the quality of 22 soft wheat cultivars across 12 southeast US locations; cultivars represented 'much of the current elite and historic germplasm grown in the Southeast.' Cultivars with exceptional PSI values were identified. Gaines *et al*[7] analyzed nine eastern and six western US soft wheat cultivars grown together in a Washington and in a Michigan environment. Their results indicated few consistent differences in grain texture (NIR hardness, and Bühler and Allis–Chalmers milling); individual cultivars were not compared. Yamamoto *et al*[8] compared 17 soft wheat cultivars representing four US market classes or sub-classes. Although individual cultivars were compared, samples came from two different crop years and four different US states. Consequently, cultivar responses were confounded with growing environment. Lin and Czuchajowska[9] compared the quality of four Club and seven soft white common winter wheat cultivars drawn from eight Washington locations over three crop years. Cultivars were among leading cultivars in terms of commercial production. The Club group of cultivars had higher NIR hardness values compared to the soft white common group, but the two groups did not differ for Bühler break flour yield. Hazen *et al*[10] examined SKCS hardness of 12 eastern US soft white and red winter wheat cultivars which fell into six groups based on multi-site analysis.

With this background, we sought to test the following hypothesis: soft wheat cultivars differ in kernel texture due to minor genetic factor(s). Before identifying specific genetic factors such as QTLs (quantitative trait loci), we first needed to test whether cultivars indeed differ, quantify those differences and identify specific cultivars that could serve as genetic material in future studies. To facilitate our expected outcome, we considered two issues as having high relevance: (1) the confounding effect of the environment must be minimized and partitioned mathematically in the statistical model; (2) since the size of the experiment must be contained, a sampling of commercial cultivars from geographical regions (origin), sub-classes and time-of-release would maximize the likelihood of identifying meaningful variation. Consequently, direct comparison of the genetic potential of selected US soft wheat cultivars was obtained by growing cultivars 'side-by-side' under identical environmental conditions in two-replicate, two-locations-per-year, 3-year field plot nurseries in Washington state.

EXPERIMENTAL

Cultivars and grain production

Thirty cultivars were selected and included in the on-going Western Wheat Quality Laboratory's (WWQL) Hall-of-Fame nursery. Their release dates ranged from 1926 to 1998 (Table 1), and were fairly evenly distributed over time with eight cultivars released before 1970, five during the 1970s, eight during the 1980s, and nine during the 1990s. Although not precise, this distribution over time provided opportunity to include less- or un-related germ plasm. (NB: quality data drawn from historical databases suffer the same confounding of kernel texture-by-environment, as noted in the Introduction. Therefore cultivars must be grown side-by-side under an identical environment). The cultivars included here were all prominent and commercially grown on a significant area, and represented white Club, eastern soft red winter, eastern soft white winter (common), and western soft white (common) wheat groups. One cultivar, 'Pomerelle', is a western soft white spring wheat but it generally survives the winter in southeastern Washington; it was therefore included in this research with the western soft white wheat group as a spring-type representative.

Description of cultivar classifications

The cultivars included in this study (Table 1) were selected to represent a sub-sample of those that have been typically grown in the eastern and western US soft wheat regions. They also were selected from the different US soft wheat market classes, sub-classes and geographical groupings. Cultivars were selected from four time periods relating to the last three decades and those released prior to 1970. The Official United States Standards for Grain[5] continues to use the botanical names *T aestivum* L and *T compactum* Host for common and Club wheats, respectively, even though *T compactum* is now generally considered a sub-species of *T aestivum*.[11] The USDA Standards further define two classes of soft wheat: Soft Red Winter wheat and Soft White wheat. There are no sub-classes in Soft Red Winter wheat; Soft White wheat has the sub-classes: Soft White wheat, White Club wheat and Western White wheat. The last of these three is simply a mixture of the other two. The standards do not differentiate eastern from western soft white wheat, nor western soft white winter from

Table 1. Cultivars used to assess kernel texture variation among US soft wheats, their classification and year of release

Cultivar	Classification[a]	Year of release	Identifier[b]	Developer[c]
Albit	Club	1926	Cltr8275	WA
Elgin	Club	1942	Cltr11755	OR
Elmar	Club	1949	Cltr12392	WA
Hiller	Club	1998	PI587026	WA
Hymar	Club	1935	Cltr11605	WA
Moro	Club	1965	Cltr13740	OR
Omar	Club	1955	Cltr13072	WA
Paha	Club	1970	Cltr14485	WA
Rely	Club	1991	PI542401	WA
Tres	Club	1984	Cltr17917	WA
Becker	SRW	1985	PI494524	OH
Coker 762	SRW	1980	Cltr17924	—
Coker 9907	SRW	1991	PI548847	—
Dynasty	SRW	1987	PI506409	OH
FFR555W	SRW	1988	—	VA
Glacier	SRW	1991	PI555586	WI
Madison	SRW	1990	PI547041	VA
McNair1003	SRW	1977	PI552975	—
Pioneer 2568	SRW	1995	PI590943	—
Pioneer 2684	SRW	1993	PI566923	—
Roy	SRW	1979	Cltr17763	NC
Geneva	ESWW	1983	PI505819	NY
Houser	ESWW	1977	Cltr17736	NY
Yorkstar	ESWW	1968	Cltr14026	NY
Brevor	WSWW	1949	Cltr12385	WA
Hill 81	WSWW	1983	Cltr17954	OR
Kmor	WSWW	1990	PI536995	WA
Lewjain	WSWW	1982	Cltr17909	WA
Pomerelle	WSWS[d]	1996	PI592983	ID
Stephens	WSWW	1977	Cltr17596	OR

[a] Classification is SRW = soft red winter, ESWW = eastern soft white winter, WSWW = western soft white winter, and WSWS = western soft white spring.
[b] Cltr and PI numbers refer to accession identifiers in the USDA-ARS National Plant Germplasm System, Germplasm Resources Information Network (GRIN).
[c] Developer identifies the state (two-letter standard US state abbreviations) in which the state university Agricultural Experiment Station, frequently in conjunction with the USDA-ARS, released the public variety. 'Coker' and 'McNair', and 'Pioneer' are branded names of the Northrup King and Pioneer Hi-Bred International Inc seed companies, respectively.
[d] For purposes of cultivar classification, 'Pomerelle' soft white spring cultivar was grouped with the western soft white winter cultivars.

western soft white spring. In commerce, western soft white winter and spring wheat grain are routinely mixed; whereas eastern and western soft white wheat grain are rarely mixed because of their geographical separation. Western white wheat either results from farmers producing the two types together (usually by over-planting soft white spring into fields of winter-injured winter Club fields) or exporter-blending to meet customer specifications. To avoid confusion, 'Classification' is used here to designate the cultivar groupings, as opposed to 'Class' which has a specific meaning in the Standards.[5]

Seed of all cultivars was obtained from the original source, a state foundation seed program or from the USDA-National Small Grains Collection in Aberdeen, ID. Original seed was grown in small field plots and rogued for purity for one year prior to the inclusion in the Hall-of-Fame (H-of-F) nursery. H-of-F nurseries were planted at Pullman and Walla Walla, WA in 1997, 1998 and 1999. In all cases, the plots were seven rows on 0.20-m centers, 3.4 m long × 1.7 m wide. All plots were later end-trimmed to 2.5 m for a total plot area of 4.25 m^2. The 30 cultivars were arranged in two replications in a randomized complete block design. Planting dates were 9 October 1996, 7 October 1997 and 5 October 1998 at Pullman; and 21 October 1996, 14 October 1997 and 14 October 1998 at Walla Walla. Seed was treated with Raxil (tebuconazole)–thiram (Gustafson LLC, Plano, TX) at labeled rates prior to planting. Plots were planted using a custom plot seeder (Plotmatic, Wintersteiger GmbH, Salt Lake City, UT). Seed was placed at a depth of approximately 0.06 m and moisture was adequate at planting for germination and seedling establishment. In order to eliminate differences in disease resistance that might impact grain development, in 1997 and 1998 all plots were sprayed with Benlate (benomyl) fungicide (Dupont, Wilmington, DE) at labeled rates (NB: Benlate is no longer labeled for application on winter wheat to control stripe rust in the USA). Stripe rust was not a production constraint for the 1999 wheat crop in Washington. Plots were also evaluated for purity and off-type plants were rogued. All plots were harvested with a Wintersteiger Nursery Master plot combine. Harvest dates were 15 August 1997, 15 August 1998 and 20 August 1999 at Pullman; and 30 July 1997, 1 August 1998 and 29 July 1999 at Walla Walla. Harvested grain from each plot was cleaned of dust, chaff and larger debris such as unthreshed florets and pieces of spike using an 'air-screen' cleaner (Air Blast Seed Cleaner model No SABSC/B, Seedburo Equip Co, Chicago, IL, USA) and a 600-g sample of the grain was used for the following kernel texture analyses.

Grain texture analyses

Kernel texture was determined by near-infrared reflectance spectroscopy (NIR) (Technicon InfaAlyzer IA-450, Bran + Lubbe, Foss North America) (Method 39–70A)[3] and the Single Kernel Characterization System 4100 (SKCS) (Perten Instruments North America, Springfield, IL) (Method 55-31).[3] Wheat moisture was determined following Method 44-16[3] and values were used to determine temper water addition. Approximately 500-g samples were tempered to 13% moisture content overnight and milled on a modified Quadrumat (CW Brabender Instruments, Inc, Hackensack, NJ) milling system following the method of Jeffers and Rubenthaler.[12] The method uses essentially a 'Senior' flow with separate break and reduction heads, and independent sifters (model 159/160, Great Western Manufacturing, Leavenworth, KS). Break flour yield was calculated based on recovered product divided by total mill products, times 100. The four fractions routinely obtained off this milling system are break flour, reduction flour, bran and shorts.

Statistical analysis

The Levene test for variance heteroscedasticity[13] indicated that environments had significantly different error variances for most traits. Therefore the combined analysis of variance over environments was conducted using weighted least-squares analysis of variance for all traits. The weighting factor was the reciprocal of the within-environment error variance. Least square means and standard errors were obtained for all traits and cultivars both within and over environments. The probability of a difference between two means was calculated. Pearson product-moment correlations were determined on trait means both within and over environments.

RESULTS

Analysis of variance (ANOVA)

ANOVA clearly indicated that cultivars differed significantly for all three kernel texture measures, SKCS, NIR and break flour yield (Table 2). SKCS had the highest model R^2 and the largest F-statistic (whole model). For all three texture measures the environment was a prominent source of variation, followed by cultivar. Variation between blocks was small and, although significant, the environment-by-cultivar interactions were of relatively minor magnitude.

Individual cultivar means for SKCS kernel hardness ranged from 11.8 for 'McNair 1003' to 42.9 for 'Hymar' (Table 3). The overall mean for all 30 cultivars was 23.4. The least significant difference (LSD) of 2.2 indicated the high precision with which cultivar means for this trait could be resolved in ANOVA. Inspecting the distribution of means revealed that 10 of the softest-ranked cultivars were from the eastern USA (SRW or ESWW, SKCS 11.8–17.7). 'Brevor' was the softest western cultivar (rank 11) and was in a DMRT group (j) with western cultivars 'Kmor' and 'Lewjain'. In total, all eastern cultivars were less than 23.8 (which is near the overall mean) in hardness and held 11 of the 14 softest-ranked positions. All western Club cultivars were harder than the overall mean, and held 10 of the 13 hardest-ranked positions. Three western soft white common cultivars were also present among the Club cultivar distribution, and were Pomerelle, 'Hill 81' and 'Stephens'.

NIR kernel hardness ranged from 9.8 for McNair 1003 to 41.7 for Hymar. On the basis of DMRT, McNair 1003 was significantly softer, and Hymar significantly harder than all other cultivars (Table 3). The overall mean NIR hardness for these 30 cultivars was 24.0, similar to the overall mean for SKCS hardness. The somewhat larger LSD of 4.4 was consistent with the lower model R^2 for this trait. Once again, the 10 softest-ranked positions were held by eastern cultivars, and 8 of these 10 were also among

Table 2. F-values[a] and summary statistics from analysis of variance for kernel texture traits of US soft wheat cultivars

Source	Degrees of freedom	SKCS kernel hardness	NIR kernel hardness	Break flour yield
Whole model	185	28.6****	5.07****	14.7****
Cultivar	29	125.3****	14.9****	62.9****
Environment	5	250.4****	57.6****	63.6****
Replicate (environment)	6	1.75	1.88	2.78*
Environment × Cultivar	145	2.61****	1.41*	3.89****
Error mean square	175	7.41	29.7	0.759
CV	—	11.6	22.7	1.80
R^2	—	0.97	0.84	0.94

[a] Where *,**,*** and **** indicate the probability of a greater F-value at $p = 0.05$, 0.01, 0.001 and 0.0001, respectively; mean squares and F-values are derived from Type III Sums of Squares.

Table 3. Kernel texture of US soft wheats as measured by SKCS, NIR and Quadrumat break flour yield, and their classification

Cultivar	Classification[a]	SKCS hardness[b]	NIR hardness[b]	Break flour yield[b]
Hymar	Club	42.9a	41.7a	46.7ghi
Stephens	WSWW	39.5b	31.3bc	44.5k
Albit	Club	37.5b	29.0bcd	47.0fgh
Elmar	Club	35.3c	33.6b	49.2de
Elgin	Club	34.3c	27.8cde	49.4cde
Tres	Club	31.3d	29.2bcd	50.2abc
Paha	Club	31.3d	29.3bcd	50.7ab
Hill 81	WSWW	29.4de	25.2def	49.5cde
Omar	Club	28.4ef	25.3def	50.8ab
Pomerelle	WSWS[c]	28.0ef	25.9def	46.4hij
Moro	Club	27.0ef	27.9cde	49.7cde
Rely	Club	26.8fg	25.4def	50.2abc
Hiller	Club	24.7gh	24.9defg	50.9a
Yorkstar	ESWW	23.8h	23.0efghi	46.8ghi
Madison	SRW	21.6i	23.3efghi	45.9j
Lewjain	WSWW	19.8ij	24.2defgh	49.1e
Coker 9907	SRW	19.7ij	19.5hijk	50.0bcd
Becker	SRW	18.9jk	17.3jk	47.3fg
Kmor	WSWW	18.8jk	22.3fghij	50.9a
Brevor	WSWW	18.0jk	22.5fghi	47.7f
Pioneer 2684	SRW	17.7jk	21.3fghij	44.8k
Dynasty	SRW	17.0kl	16.2k	49.0e
Roy	SRW	15.3lm	19.8ghijk	51.0a
Coker 762	SRW	14.8lmn	18.8ijk	50.6ab
FFR555W	SRW	14.7lmn	19.3hijk	45.7j
Pioneer 2568	SRW	13.7mno	14.9k	46.7ghi
Geneva	ESWW	13.6mno	24.4defgh	49.6cde
Glacier	SRW	13.4mno	25.0defg	49.0e
Houser	ESWW	12.8no	21.8fghij	50.0bcd
McNair1003	SRW	11.8o	9.8l	46.1ij

[a] Classification is described in Table 1.
[b] Means followed by the same letter within a column are not significantly different based on Duncan's multiple-range test ($\alpha = 0.05$).
[c] For purposes of cultivar classification, 'Pomerelle' soft white spring cultivar was grouped with the western soft white winter cultivars.

the softest 10 cultivars based on SKCS hardness. Among the somewhat larger group of 15 softest-ranked cultivars, 11 were of eastern origin, with Kmor, Brevor and Lewjain again being the softest western cultivars. As observed for SKCS hardness, the western Club wheat cultivars were all harder than the overall mean, and held 10 of the 14 hardest ranks. With the exception of Hiller, the softest Club cultivar, the other Club cultivars held the hardest 9 out of 11 ranks. Stephens and Pomerelle were again present in this group and were the hardest western soft white common cultivars.

Correlation analysis indicated that SKCS and NIR hardness values were correlated at $r = 0.85$ ($p < 0.001$). A plot of the data (Fig 1) revealed that the cultivars arrayed themselves along the least-squares regression line in some observable patterns. These patterns included a separation (indicated by the arrow on Fig 1) between the western Club cultivars and all of the eastern cultivars. The western soft white common cultivars had a greater distribution in hardness. A second pattern was that all but one soft red winter cultivar were on or below the least-squares line, indicating that, among this specific group of cultivars, they tend to have lower NIR hardness at a given SKCS hardness level. A second observation relative to this group of SRW cultivars is that their SKCS and NIR hardness values tend to be more similar. In this respect, it should be noted that the least-squares line does not pass through the origin nor have a slope of one. (The least-squares fit equation is $\text{NIR} = (\text{SKCS} * 0.57) + 10.6$, $r^2 = 0.71$). When the 'unity' line is applied to the data set (data not shown), it becomes evident that the majority of the Club cultivars lie below the line, indicating that their NIR hardness is lower relative to their SKCS hardness.

The greatest changes in ranking between SKCS hardness and NIR hardness were observed for the eastern soft cultivars 'Glacier', 'Geneva' and 'Houser' which moved from softer to harder ranks: they were in the 3rd, 4th and 2nd softest SKCS ranks, respectively, but moved up to the 18th, 16th and 10th softest NIR ranks, respectively. The greatest change in rank going from harder to softer were again eastern cultivars: 'Coker 9907', 'Becker' and 'Dynasty' going from 14th, 13th and 9th softest to 7th, 4th and 3rd softest, respectively.

Break flour yield was highest for 'Roy' and lowest for 'Stephens'. The overall range was 44.5–51.0%, with a mean of 48.5%. Club wheat cultivars held 8 of the highest 15 ranks. ('Hymar' Club was notably down at rank 23). In addition to 'Roy', other notable cultivars in the top DMRT group were the western soft white common cultivar 'Kmor' at rank 3, and the eastern SRW cultivar 'Coker 762' at rank 6.

A 'diagonal unity' plot showed the spatial distribution of break flour yields (Fig 2). Two distinct discontinuities were apparent: the first between 47.7 and 49.0%, the second between 44.8 and 45.7%. These 'gaps' were supported by DMRT separations as well. In the highest break flour yield group (DMRT groups a, b, c, d, and e), in addition to the eight Club cultivars plus 'Roy', 'Kmor' and 'Coker 762', were 'Houser', 'Coker 9907', 'Geneva', 'Hill 81', 'Lewjain', 'Glacier' and 'Dynasty'. 'Stephens' was in the lowest break flour yield group with 'Pioneer 2684'.

It was surprising that break flour yield was not significantly correlated with SKCS and NIR hardness ($r = -0.07$ and 0.07, respectively). A plot of NIR hardness versus break flour yield (data not shown) revealed little beyond the discontinuities in break flour yield described above (Fig 2). A plot of SKCS hardness versus break flour yield indicated that the cultivars could be placed in specific groups (Fig 3). The first of these groups, in the upper right section of the plot, represented cultivars with higher SKCS hardness (greater than the overall mean) and higher break flour yield (above the 'discontinuity gap' >49%). Included in this group were all Club wheat cultivars except 'Albit' and 'Hymar'. 'Albit' and 'Hymar' are

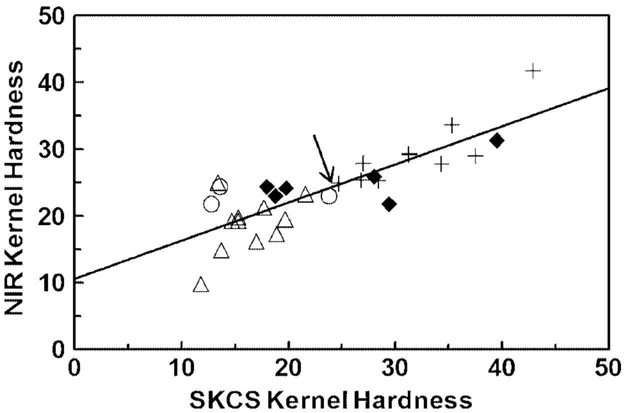

Figure 1. SKCS kernel hardness versus NIR kernel hardness for 30 eastern and western US soft wheat cultivars grown in Washington state. Each data point is the mean of 12 observations (2 replicates × 2 sites × 3 years); 'plus' = soft white Club, 'triangle' = soft red winter, 'circle' = eastern soft white winter, and 'diamond' = western soft white wheat cultivars. The arrow indicates the separation point of eastern cultivars from Club cultivars.

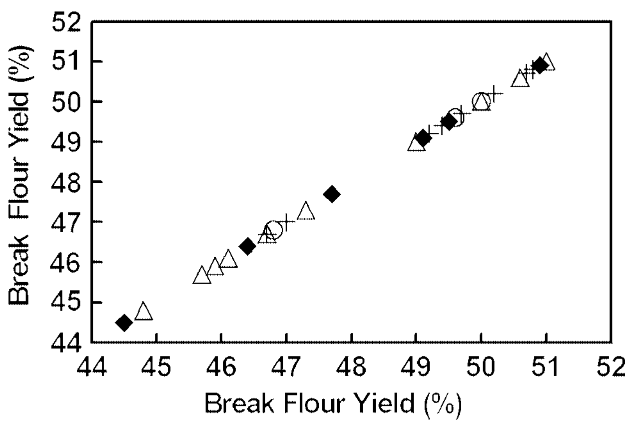

Figure 2. "Diagonal Unity Plot" of Quadrumat break flour yield for 30 eastern and western US soft wheat cultivars grown in Washington state. Each data point is the mean of 12 observations; 'plus' = soft white Club, 'triangle' = soft red winter, 'circle' = eastern soft white winter, and 'diamond' = western soft white wheat cultivars. The upper 'gap' occurs from 47.7 to 49.0%.

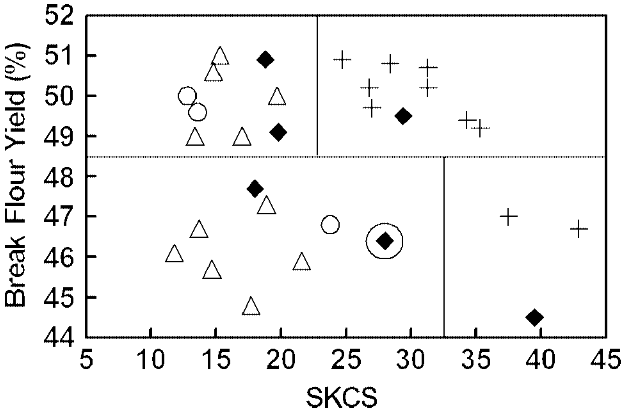

Figure 3. SKCS kernel hardness versus Quadrumat break flour yield for 30 eastern and western US soft wheat cultivars grown in Washington state. Each data point is the mean of 12 observations; 'plus' = soft white Club, 'triangle' = soft red winter, 'circle' = eastern soft white winter, and 'diamond' = western soft white wheat cultivars. Lines are placed on the figure to indicate cultivar groupings based on ANOVA mean separations (see Results). The Circled diamond is 'Pomerelle' soft white common spring wheat.

notably the oldest Club cultivars and pre-date the 1940s (Table 1). Included in this group of 'higher SKCS/higher break flour yield' cultivars is one western soft white common cultivar, 'Hill 81'. The second grouping identified on Fig 3 in the lower right section included 'Albit', 'Hymar' and the western soft white common cultivar 'Stephens'. These three cultivars had high SKCS hardness and low break flour yield. Similar to these cultivars in break flour yield but of somewhat softer SKCS hardness was the western spring wheat cultivar 'Pomerelle' (diamond circled on Fig 3). The last two groupings, both of which were characterized as having lower (softer) SKCS hardness values, were separated by the 'gap' in break flour yield (47.4–49.0%) described above. Both of these groupings were predominantly eastern cultivars, and all eastern cultivars were present in one or the other group. However, at least two western soft wheat cultivars were also present in each group.

DISCUSSION

As expected, the soft wheat cultivars in this study differed significantly in kernel texture. By 'removing' environmental effects through experimental design and statistical analysis, we resolved what would be considered heritable (and therefore) minor genetic differences in kernel texture. Although kernel texture is recognized as one of the leading traits that determines end-use quality, variation within hardness (puroindoline) class is poorly understood and kernel hardness itself has no absolute definition. We employed SKCS, NIR and Quadrumat break flour yield as phenotypic measures of kernel texture. Although usually well inter-correlated in studies involving soft and hard wheats, among the soft wheats examined here, only SKCS and NIR were reasonably-well correlated ($r = 0.85$, $p < 0.001$). Neither SKCS nor NIR hardness measure was correlated with break flour yield. Previous work found similar results: SKCS and NIR were highly correlated, but neither was correlated with break flour yield.[14,15] This fact indicates that flour granulation from the mill is different than either the crushing resistance on the SKCS or the granulation resulting from the UDY grinder and the resultant spectral characteristics in the NIR. Also, it is noteworthy that break flour yield includes a timed sieving separation. In this last sense, 'McNair 1003' was noted as being especially soft in SKCS and NIR, but was considered a poor milling wheat[16] and its break flour yield was near the lower limit of the range (Table 3). A cultivar such as 'McNair 1003' may produce flour particles that do not sift or flow easily, traits that are considered undesirable by millers.

Although clear genetic differences exist among cultivars, environment is nevertheless an important consideration in kernel texture. In this research the environment effect was of similar magnitude to the cultivar effect (Table 2). However, the relatively small cultivar-by-environment interaction indicated that all cultivars respond similarly to environmental cues. Washington state is notable in the sense that 'unadapted' wheat cultivars can be grown easily and produce high quality well-filled grain. Foliar diseases were controlled when necessary and all cultivars headed within a few days of each other. Because of these features, we consider the differences in kernel texture observed here to be truly the result of differences in genes expressed during seed development and not some pleitropic effect of agronomic, adaptation or disease resistance genes.

The four geographical/sub-class cultivar classifications tended to differ genetically. However, cultivars within each classification were by no means uniform for kernel texture. Trends or generalized features of these classifications may reflect the conservative germ plasm bases that underlie most breeding programs, and the separation of these classifications geographically and temporally in the USA. However, it is important to point out that at least one member of the various classifications appeared in most groupings (Fig 3), and therefore we consider any target group, for example high break flour yield and soft SKCS hardness, is attainable in any region or sub-class.

These results indicate the existence of different minor gene(s) among these cultivars for kernel texture or macromolecular composition that could potentially be exploited in wheat improvement. This 'within-soft-class' variation should become increasingly important as wheat improvement and breeding targets are refined.

In conclusion, kernel texture is an important consideration for soft wheat improvement. Here, 30 soft wheat cultivars drawn from the four major US soft wheat germ plasm pools were selected, and were evaluated in 'head-to-head' replicated multiple-site and multiple-year trials. Significant differences in kernel texture traits (SKCS, NIR and break flour yield) were found to exist among cultivars. The underlying genetic source(s) of these phenotypes are unknown and will require further inquiry. Some of the cultivars described here may prove useful as sources of exceptional kernel softness for crossing and research purposes.

ACKNOWLEDGEMENTS

Dr Harold Bockelman, USDA-ARS-NPGS is thanked for providing some of the seed stocks of cultivars included in this study. The contribution of Doug Engle, Art Bettge, John Pritchett and Lynn Little is gratefully acknowledged.

REFERENCES

1 Morris CF and Rose SP, Wheat, in *Cereal Grain Quality*, ed by Henry RJ and Kettlewell PS. Chapman & Hall, London, Chapter 1, pp 3–54 (1996).
2 Morris CF, Puroindolines: the molecular genetic basis of wheat grain hardness. *Plant Molec Biol* **48**:633–647 (2002).
3 AACC, *Approved Methods of the American Association of Cereal Chemists*, 10th edn. American Association of Cereal Chemists, Saint Paul, MN (2004).
4 Bacon RK, US Soft Winter Wheat Pool, in *The World Wheat Book: A History of Wheat Breeding*, ed by Bonjean, AP and Angus WJ. Lavoisier Publishing, Paris, pp 469–478 (2001).
5 USDA, *Official United States Standards for Grain*. Federal Grain Inspection Service, US Department of Agriculture, Riverdale, MD (1996).
6 Baenziger PS, Clements RL, McIntosh MS, Yamazaki WT, Starling TM, Sammons D.J. and Johnson JW, Effect of cultivar, environment, and their interaction and stability analyses on milling and baking quality of soft red winter wheat. *Crop Sci* **25**:5–8 (1985).
7 Gaines CS, Finney PL and Rubenthaler GL, Milling and baking qualities of some wheats developed for eastern or northwestern regions of the United States and grown at both locations. *Cereal Chem* **73**:521–525 (1996).
8 Yamamoto H, Worthington ST, Hou G and Ng PKW, Rheological properties and baking qualities of selected soft wheats grown in the United States. *Cereal Chem* **73**:215–221 (1996).
9 Lin PY and Czuchajowska Z, Starch properties and stability of club and soft white winter wheats from the Pacific Northwest of the United States. *Cereal Chem* **74**:639–646 (1997).
10 Hazen SP, Ng PKW and Ward RW, Variation in grain functional quality for soft winter wheat. *Crop Sci* **37**:1086–1093 (1997).
11 Slageren MW van, *Wild Wheats: A Monograph of* Aegilops *L and* Amblyopyrum *(Jaub & Spach) Eig (Poaceae)*. Wageningen Agricultural University, Wageningen, The Netherlands & International Center for Agricultural Research in the Dry Areas (2004).
12 Jeffers HC and Rubenthaler GL, Effects of roll temperature on flour yield with the Brabender Quadrumat experimental mills. *Cereal Chem* **54**:1018–1025 (1977).
13 Schabenberger O and Pierce FJ, *Contemporary Statistical Models for the Plant and Soil Sciences*. CRC Press, Boca Raton, FL (2001).
14 Giroux MJ and Morris CF, A glycine to serine change in puroindoline b is associated with wheat grain hardness and low levels of starch-surface friabilin. *Theor Appl Genetics* **95**:857–864 (1997).
15 Morris CF, DeMacon, VL and Giroux MJ, Wheat grain hardness among chromosome 5D homozygous recombinant substitution lines using different methods of measurement. *Cereal Chem* **76**:249–254 (1999).
16 Morris CF, Campbell, KG and King GE, Characterization of the end-use quality of soft wheat cultivars from the eastern and western US germ plasm pools. *Plant Genetic Resour* **2**:59–69 (2004).